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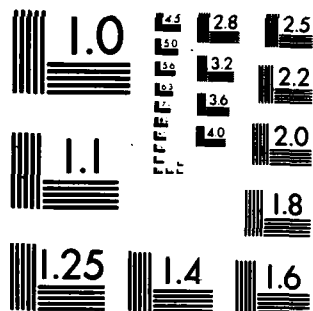   AFGL-TR-83-0200
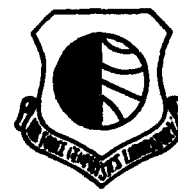
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Melting Layer Survey - Final Report

IAN D. COHEN, Capt, USAF
HUGH J. SWEENEY

12 August 1983

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Research involving the region of clouds in which snowflakes and ice crystals melt is reviewed. Studies of how ice crystals and snowflakes melt are examined and show that in general, melting is slower and less structured then was previously realized. An investigation of the radar bright band is included. The increase of returned signal from the melting particles in the bright band comes from the increase of the index of refraction when the particles turn from snow to water. This is not a radar/particle-surface phenomenon, but it is a radar/particle-density interaction. Thus the bright band does not begin at the

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top of the melting layer as the particles first begin to melt but appears at a lower level when a sufficient mass has melted.   The literature survey presented in AFGL-TR-82-0007 is revised and expanded.

Preface

This report summarizes work done under in-house work unit 2310G502. Special thanks are due to Lt. Col (Ret.) Robert Schaller, who, while at AFGL, organized this work unit and planned the program.

Outside of AFGL, several other individuals and groups worked with us on this project. Most notable among these were Professor Richard Passarelli and Dr. K. Kenneth Lo of the Massachusetts Institute of Technology, Professor Steven B. Newman of Central Connecticut State College, and Dr. Norihiko Fukuta of the University of Utah.

The authors would like to thank Dr. Arnold Barnes, Jr. for his suggestions and assistance in preparing this report, and Mrs. Carolyn Fadden for typing the manuscript.

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Melting Layer Survey—Final Report

1. INTRODUCTION

The AFGL Melting Layer study was begun in 1979. Original plans called for a
flight program and extensive radar studies. Budget problems and a change in the
AFGL meteorology program led to curtailment of these portions of the program.
This report will therefore concentrate on those portions of the program that were
completed. They include:

    (1) A survey of past and present research on the melting layer,

    (2) Theoretical and observational studies of the melting of ice crystals
        and snowflakes,

    (3) The radar "bright band" and its relation to the melting layer.

Schaller et al[1] summarized the work done during the early phases of this study.
Since that time, some additional work has been done as part of the AFGL program,
and much has been done outside of AFGL. Section 4 of this report will review this
work.

No further effort to define boundaries of the melting layer have been made.
Rather, the AFGL study has focused on the melting layer as a transition region with
no fixed limits.

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1. Schaller, R. C., Cohen, I. D., Barnes, A. A., and Gibbons, L. C. (1982) A
    Survey of Melting Layer Research, AFGL-TR-82-0007, AD A11524.

Interest in the melting layer has remained high. Stewart,[2] showed how important the processes in this region can be to precipitation. Cohen[3] found a considerable amount of aircraft icing near the 0°C isotherm, including a few cases of icing at temperatures between 0°C and +2°C. Reports by Newman[4] and Lo and Passarelli[5] have added to their work. Further efforts by Mr. Hugh Sweeney and Dr. Norihiko Fukuta will be discussed later in this report.

The structure of ice and the melting process have been the subject of several studies. Fukuta[6] and Rasmussen et al[7] have reported on studies of the melting of ice crystals. The former developed a theoretical model of snowflake melting, while the latter the latter conducted wind tunnel tests which showed that a ring of water will form at the equator of a spherical ice particle.

Radar continues to be used as a tool to examine the melting layer. Bohren and Battan[8] have noted the effect partially melting crystals, and crystals with a "spongy" outer layer, have on radar reflectivity. Bringi et al[9] explain how dual polarization can be used to identify precipitation particles. The use of Doppler radar is certain to add to our knowledge of the melting layer. Metcalf[10] discusses polarization diversity radar; another technique which will help us understand this region.

Thus, although the AFGL study of the melting layer has been completed, research into this area of the atmosphere is continuing, and will lead to new dis- coveries which will be of great interest to meteorologists.

2. LITERATURE SURVEY

Schaller et al[1] provided a list of reports on previous melting layer research. An expanded list is included in Appendix A of this report. The list includes 49 addi- tional entries on the subjects of scattering, theory and applications of radar, and laboratory studies of ice, water, and melting. Some, such as Battan[11] have been included to provide additional background material. Others, such as Kinzer and Cobb[12] and Kinzer,[13] are on laboratory studies which apply to processes which occur in the melting layer.

Most of the additions to the list represent works published since the previous version of the list was compiled. In addition to Fukuta et al,[6] work by Donovan[14] and Savage[15] was sponsored by AFGL. Most of the work in recent years has in- volved wind tunnel studies such as Rasmussen and Pruppacher[16] or radar observa- tions using new techniques, such as the dual-polarization studies by Krehbiel and Broch[17] and Kropfli et al.[18] The full updated bibliography is presented in Appendix A.

(Due to the large number of references cited above, they will not be listed here. See References, page 23.)

3. ICE CRYSTAL AND SNOWFLAKE MELTING

Fukuta[6] used the melting chamber shown in Figure 1 to study the melting of
snowflakes and ice crystals. The chamber was mounted on a truck and could be
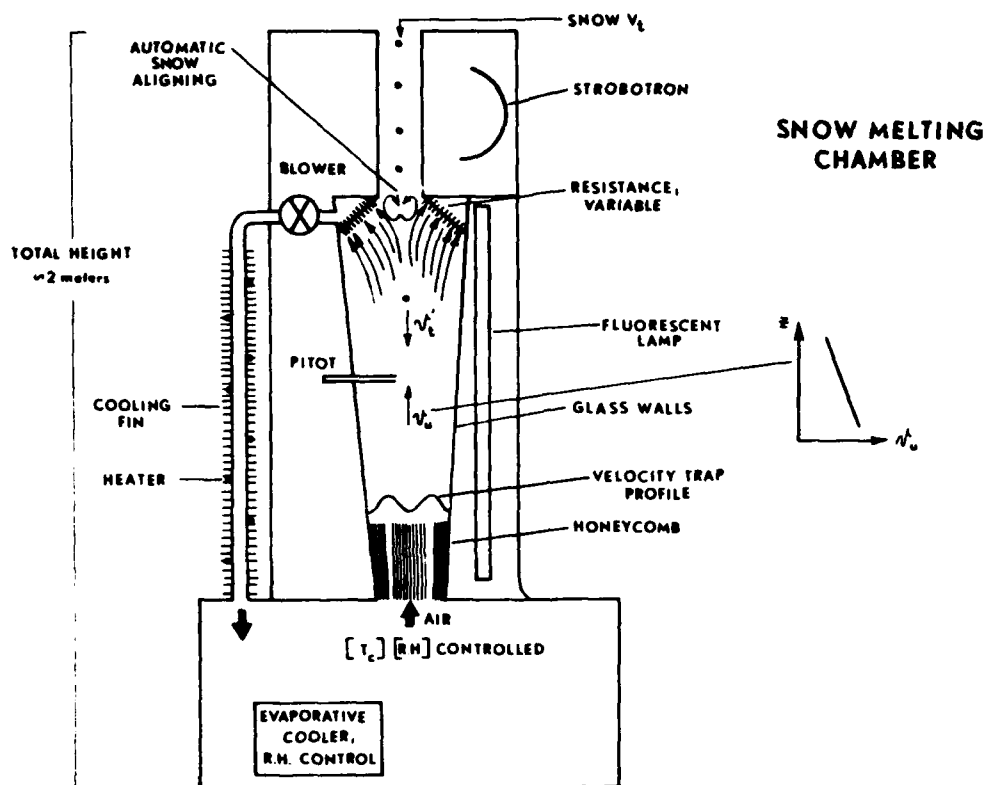moved to various locations to enable him to observe snowflakes in different locations.

Figure 1. University of Utah Melting Chamber. This chamber was used to
study the melting of 2700 ice crystals and snowflakes

As a general rule, snowflakes begin to melt from the outside. As they do, the
radius of the flake changes. In addition, a coating of water forms on the outside of
each ice crystal. The exact shape may vary with the type of crystal. While Fukuta
et al[6] note that the water may form into an oblate spheroid, Rasmussen et al[7] report
that meltwater from larger spherical crystals forms a torus at the equator of the
crystal. Regardless of the shape, a layer of water on the outside of a snowflake can
affect the type of radar return it will exhibit. The water will also cause other par-
ticles to adhere to the snowflake, thus causing aggregates.

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One surprising thing about the melting of snowflakes was that the ice skeleton which remains below the liquid coating would often disintegrate in an irregular pattern. While smaller crystals (up to 1 millimeter in diameter) could easily be suspended in the wind tunnel, larger ones often moved in unexpected directions and generally were lost before they had completed the melting process.

Donovan[14] summarized the major findings of the observation program as follows:

(1) The observed melting time of snowflakes increased with size, but rather gently. The increase was far slower than that predicted by current theory.

(2) Snow crystal disruption, in which a crystal melts not into a spherical water droplet, but into several pieces, was confirmed. This phenomenon was observed to be a dominant factor in the melting of snowflakes/crystals, rather than an occasional occurrence, as had been previously thought.

(3) The vertical stability of a suspended snowflake appeared to be dependent upon its size and shape. Small crystals, less than 1 mm in diameter, were the most stable.

(4) Helicoptering, or the rotation of a crystal around its vertical axis, was observed in crystals 1-3 mm in diameter.

(5) Crystals 1-3 mm in diameter went into a "death spiral" crashing into the wall of the chamber during the last portion of their melting process.

(6) Crystals less than 1 mm in diameter jumped violently at the end of their melting process. This jump was usually upwards or to the side, but seldom downwards.

(7) Large, flat, symmetrical dendritic crystals (less than 0.3 mm thick) fell flat and were very stable in the chamber airstream. They melted, as the current theory predicted, from the outside inwards. There was no disruption observed with these crystals.

(8) The snowflake's shape changed gradually while the melting proceeded. The shape change appeared faster in the subsaturated environment. A final shape was never observed, however, since crystals frequently broke into smaller pieces while they were melting.

Savage[15] noted that individual crystals melt at a rate which varies with the crystal size. He also noted that the crystals disintegrate as they melt and melt more rapidly as they disintegrate.

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Matsuo and Sasyo[19] studied the melting of ice and snow pellets. They observed that the melting of snow in the atmosphere depends on air temperature, relative humidity, pellet size, and density. They note that snow will melt faster in saturated air since latent heat of condensation will be released as water condenses on the particle. In sub-saturated air, however, the pellet will try to sublimate, and thus try to absorb heat, therefore, cooling the pellet.

4. RADAR OBSERVATIONS OF THE MELTING LAYER

Early observations with vertically scanning radar revealed a   .ci ?ase in echo intensity in a narrow altitude range near the zero-degree isother   melting layer). This feature has been named the "bright band" by radar meteoro' ·sts. Studies of the bright band and the area near it have continued through the y   Ekpenyong and Srivastava[20] carried out a theoretical study of the radar cha. ᵉ   .stics of the melting layer with the following assumptions:

(1) The melting layer is assumed to have a steady thermal structure with a constant lapse rate which does not vary with time.
(2) A steady supply of snowflakes of prescribed size distribution is maintained at the 0° C level, that is, at the top of the melting region.
(3) There is no aggregation or breakup of snowflakes in the melting region.
(4) Snowflakes have spherical shapes.
(5) The melted water forms a coat around the snowflake.
(6) Growth by collision and coalescence with cloud drops and by condensation of water vapor is ignored.

They concluded that the comparison of their theoretical results with observations indicated that aggregration and breakup of melting snowflakes is a distinct possibility.

They also conclude that the temperature lapse rate may be larger than assumed in their model in the lower parts of the melting layer.

Snowflakes and aggregates are known to be non-spherical and these authors suggest that polarization measurements be made in order to assess the effects of the non-spherical geometry of the scatterers.

19. Matsuo, T., and Sasyo, Y. (1982) Melting of snow pellets in the atmosphere, Papers in Meteor. and Geophysics, Tokyo, No. 33:55-64.

20. Ekpenyong, B., and Srivastava, R. (1970) Radar Characteristics of the Melting Layer-A Theoretical Study. University of Chicago Department of Geophysical Sciences and Illinois Institute of Technology, Department of Electrical Engineering, Technical Report No. 16, Lab. for Atm. Probing, Chicago, Illinois.

Wexler[21] suggests breaking the melting layer into two zones:

(1) Zone 1 extends from the 0° C isotherm to the peak of the radar reflectivity in the bright band.

(2) Zone 2 extends from the peak of the radar reflectivity in the bright band to that point at which the snowflake is completely melted (that is, raindrops reach terminal velocity and radar reflectivity becomes nearly constant with height).

Figure 2 shows an idealized model of the melting layer based on the six assumptions noted, with snow above and rain below the freezing level. The plotted values for mean particle fall velocity, radar echo power, and melting band thickness are approximate values only. For example, we know that the peak echo power in the center of the bright band is normally 12-15 dB greater than in the snow above and 5-10 dB greater than in the rain below as schematically presented in Figures 2 and 3.
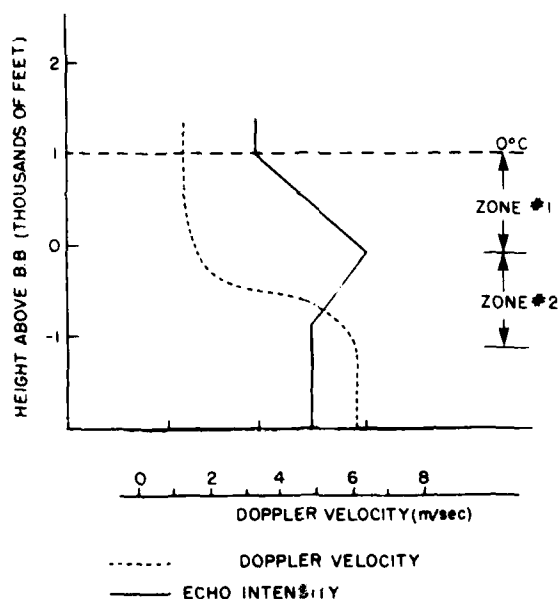

Figure 2. Idealized Model of the Melting Layer.
This model divides the melting layer into two
zones separated by the maximum of the radar
return intensity

21. Wexler, R. (1955) An evaluation of the physical effects of the melting layer. Proceedings, Fifth Weather Radar Conference, American Meteorological Soc., Ft. Monmouth, New Jersey, Sept 1955, pp 329-334.
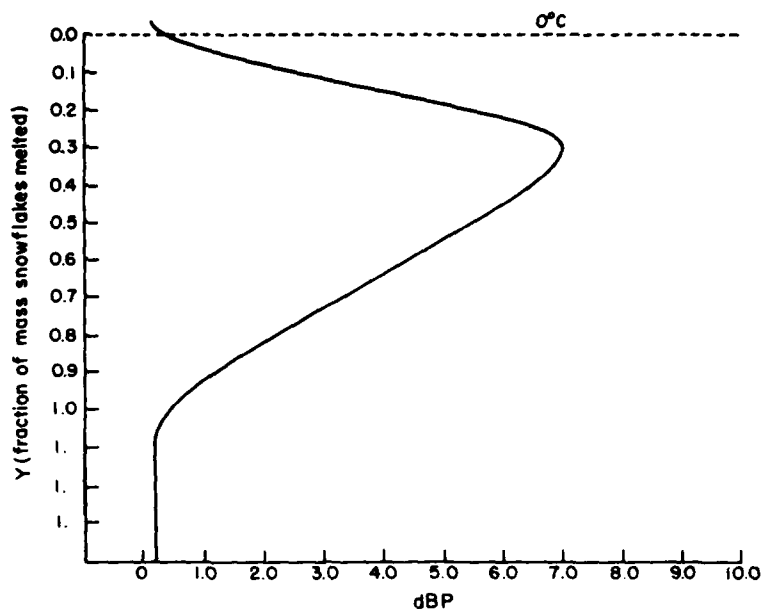
Figure 3. Power Received vs Mass Melted. From simplified model using change of index of refraction and change of fall speed from snow to rain

Based on the work of Ekpenyong and Srivastava[20] and Wexler,[21] the following model can be defined.

4.1 Calculations

In Zone 1 we assume that melting takes place from the outside-in. The snow particles are becoming smaller but $|K|^2$ (K is the complex index of refraction) is changing from that for ice (0.18) to that for water (0.93):

$$|K|^2 = \frac{|\epsilon^2 - 1|^2}{|\epsilon^2 + 2|}$$

where

ϵ = dielectric constant,

K = complex index of refraction

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and

$$|K_w|^2 = 0.930, \quad |K_i|^2 = 0.18.$$

Let us assume that the mass of the snowflakes does not change as it melts. We define

D_m = diameter of equivalent melted water drops,

D_o = diameter of snowflakes,

$$Z = \sum_{vol} D_m^6.$$

For large snow, (which generally occurs at the top of the melting layer) Cunningham[22] found that

$$D_m = 0.4 \, D_o^{0.782}.$$

Now the radar received power (P_r) is given by

$$P_r = Cr^{-2} |K|^2 Z$$

where

C = radar constant for individual radars

r = distance between radar and particle.

For a completely melted snowflake,

$$P_r(\text{water}) = Cr^{-2} |K_w|^2 D_m^6$$

22. Cunningham, R. M. (1978) Analysis of particle spectral data from optical array (PMS) 1-D and 2-D sensors. Preprints, Fourth Symposium on Meteorological Observations and Instrumentation, American Meteorological Soc., Denver, Colorado, 10-14 Apr 1978, pp 345-350.

and for the unmelted snowflake,

$$P_r(\text{ice}) = Cr^{-2}|K_i|^2 (0.4 D_o^{0.782})^6$$

$$= Cr^{-2}|K_i|^2 D_m^6 .$$

The increase in signal strength due to melting of the snowflake is

$$\frac{P_r(\text{water})}{P_r(\text{ice})} = \frac{|K_2|^2}{|K_i|^2} = \frac{0.93}{0.18} = 5.17$$

or 7.1 dB. This derivation depends on the assumption that the returned radar signal is a function of the water mass of the snowflake. According to Ekpenyong and Srivastava[19] when 1/3 of the original volume of ice has melted into this film of water, the index of refraction will have changed from that for ice to that for water.

If at this point, there is any air inside the circumscribed sphere making the diameter of the circumscribed sphere greater than D_m and if the radar scattering process is to any extent a surface phenomenon as opposed to a mass property, then there could be an increase of P_r above and beyond that due to the ice/water phase change.

If one-third of the mass has melted then $(D_n)^3 = 2/3 (D_o)^3$ and the partially melted snowflake has a diameter of

$$D_n = (2/3)^{1/3} D_o = 0.87 D_o .$$

If it is encircled with water, then

$$P_r(n) = Cr^{-2}|K_w|^2 D_n^6$$

$$= Cr^{-2}|K_w|^2 (0.87 D_o)^6$$

$$= Cr^{-2}|K_w|^2 [0.87 (D_m/0.4)^{1.28}]^6$$

and

$$\frac{P_r(n)}{P_r(\text{water})} = [0.87 (D_m/0.4)^{1.28}]^6 (1/D_m^6) = 494 \times D_m^{1.68} .$$

For D_m greater than 0.25 mm there would be an increase in signal.

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For $D_0 = 10$ mm to 1.0 cm diameter snow, the increase would be approximately

$$\frac{P_r(n)}{P_r(water)} = \frac{(0.87\,D_0)^6}{D_m^6} = 2152$$

or 33 dB. Since this type of increase is not seen when using 5- and 10-cm wavelength radars, we must conclude that the return power is a mass and not a surface phenomenon for these wavelengths.

This means that if the mass of the snow particle does not change as it melts, the increase in radar received power (P) is due to the change in the complex index of refraction $|K|^2$ from ice (0.18) to water (0.93). The decrease of echo intensity below the bright band level is then the result of decreases of particle concentration caused by increases of fall velocity as the particles melt. The increase in velocity is about 5 to 1 (a typical case) and the concentration decreases in the same ratio. This change alone will account for a 7 dB decrease in echo intensity for the radar sampled volume at the bottom of the melting layer (Figure 3).

4.2 Generation of the Bright Band

In the basic melting layer model presented above, the bright band radar signal is generated by ice aggregate particles melting within the layer. The increase in echo intensity (Zone 1) is caused by the change in value of the complex index of refraction from that of ice to that of water. The decrease in signal intensity in Zone 2 is attributed to the increase in fall velocity in the melting layer as the particles complete melting. Figure 4 shows the fall velocities for snowflakes. The equations used to construct the figure are included. Not all of the processes involved are completely defined by accepted equations. Many of the parameters of the melting layer can be generated mathematically once one knows the particle size distribution entering the melting layer and the temperature lapse rate within the layer, but we know this is not a steady-state system and the internal dynamics of the melting layer must be included. In a melting layer with a steady-state thermal structure, the melting process described earlier contributes approximately 7 dB of signal intensity to the radar echo.

Numerous radar studies of the bright band show that at times the signal enhancement exceeds 7 dB, normally 12 to 15 dB. In these cases, other processes must contribute to signal enhancement. Some possible processes are discussed below.
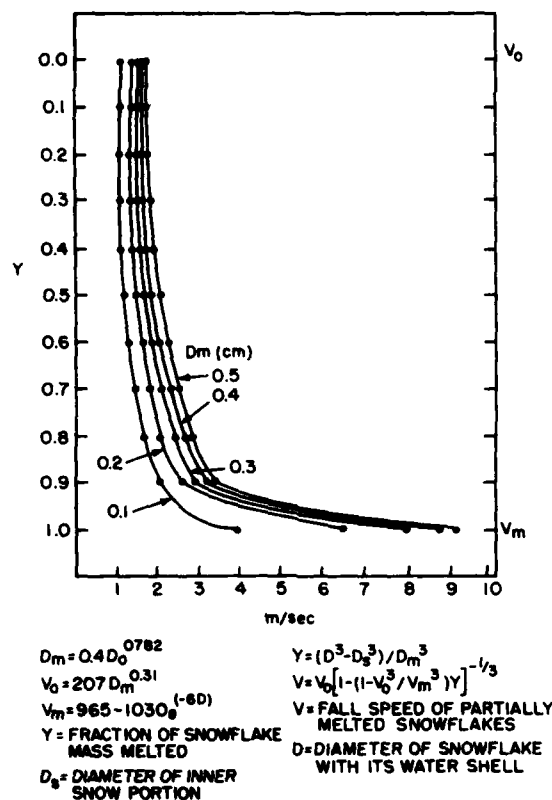
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$D_m = 0.4 D_0^{.0782}$

$V_0 = 207 D_m^{0.31}$

$V_m = 965 - 1030 e^{(-6D)}$

$Y = $ FRACTION OF SNOWFLAKE MASS MELTED

$D_s = $ DIAMETER OF INNER SNOW PORTION

$Y = (D^3 - D_s^3)/D_m^3$

$V = V_0 \left[1 - (1 - V_0^3/V_m^3) Y \right]^{-1/3}$

$V = $ FALL SPEED OF PARTIALLY MELTED SNOWFLAKES

$D = $ DIAMETER OF SNOWFLAKE WITH ITS WATER SHELL

Figure 4. Mass Melted vs Fall Velocity,
Note the changes in fall velocity (v), as
melting (y) nears completion

4.3 Processes in Zone 1

Any process which causes a growth in the mass (M) of a particle in Zone 1
would affect Z, the radar reflectivity, since Z is a function of M^2. Possible pro-
cesses here are aggregation, collision, coalescence, and deposition. Estimates of
the relative magnitude of these effects are dependent on the meteorological condi-
tions existing during the measurement exercise.

Another possible process in Zone 1 is concerned with signal strength variations
due to the shape and orientation of scatterers in the bright band in relation to the
polarization of the incident radiation. In conventional radar systems, the only
component of the received signal that reaches the radar is that which is polarized
in the same plane as the incident wave so that T_{xx} (intensity at the same polarization)
is a measure of the echo intensity to be expected in the main channel of the receiver.

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Spherical particles reflect all of the backscattered radiation with a polarization parallel to the transmitted polarization T_{xx}. Non-spherical particles reflect some portion of the scattered radiation with a polarization orthogonal to that of the transmitted radiation.

A theoretical study by Labrum[23] of melting ice particles shows that the increase in T_{xx} caused by melting is much greater for clouds of non-spherical ice particles than for clouds of ice spheres. This is illustrated in Figure 5. The backscatter intensity of non-spherical particles on melting increases in backscatter intensity stops and then starts to decrease until it ends when the particles finally become spherical waterdrops. A radar observation at vertical incidence at the height of the maximum depolarized backscatter was presented by Krehbiel and Brock.[17] These measurements indicate that the small particles with fall speeds of 3-4 m sec^{-1} had an orthogonal polarized backscatter that was 22-24 dB below the backscatter parallel to the transmitted polarization, that is, these particles appear almost spherical to the radar. Since these particles are primarily wet (partially melted) snow, the fall speeds are somewhat faster than those often observed with dry snow. At larger Doppler velocities, however, the orthogonally polarized backscatter was relatively stronger, being only about 10 dB below the parallel-polarized backscatter. This means that the larger particles with fall speeds of 4.5-9.0 m sec^{-1} appeared more non-spherical to the radar. These particles, however, were the source of only a small fraction of the total received power in either polarization at this height. The use of this type of data to describe fully the evolution of hydrometeor types, sizes and number concentrations through the melting layer requires a full set of observations of the type taken at the center of the maximum orthogonal return, extending from well above to well below the zero degree isotherm. Several investigators have observed the entire melting layer with dual polarization backscatter measurements, (for example, Humphries and Barge[24]). These show that the maximum depolarized backscatter occurs about 100-300 m below the maximum reflectivity in the bright band. This means the value of the index of refraction factor $|K|^2$ of the particles falling through the melting layer changes from that of ice to that of water before the large nonspherical particles begin to collapse. It also means that the portion of depolarized backscatter radiation coincident in time and space with the maximum reflectivity in the bright band does not contribute to this peak bright band return. Recent studies of the melting of large ice spheres, by Rasmussen, Levizzani and Pruppacher[7] show that when an ice sphere melts,

23. Labrum, N. (1952) The scattering of radio waves by meteorological particles, J. Appl. Phys. No. 12:1324.

24. Humphries, R.G., and Barge, B.L. (1979) Polarization and dual wave length radar observations of the bright band. IEEE Trans. Geoscience Electronics GE-17(No. 4):190-195.

the meltwater from the lower half of the particle is advected into a torus near the equator of the particle. This ring torus of accumulated water changes the overall shape of the original spherical particle to a distorted oblate spheroid. This change in shape due to melting agrees well with the change in large particles observed by the coherent dual polarized radars. The overall shape of small melting ice spheres remains spherical, which agrees well with the coherent dual polarized radar observation.
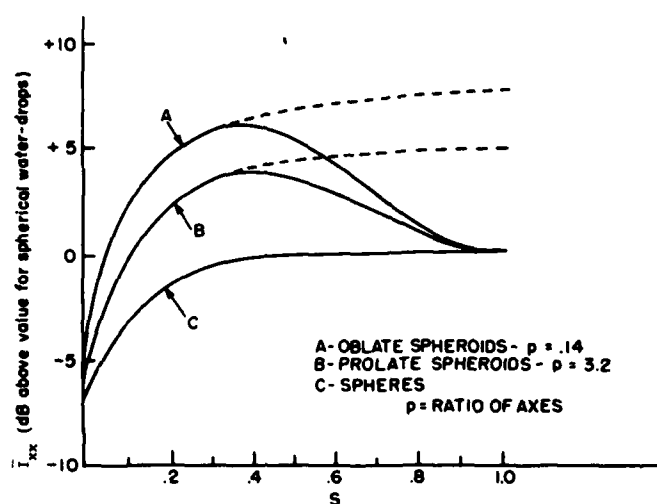

Figure 5   Changes in Back Scattering From Cloud During Melting. S = melting ratio. Broken lines represent variation assuming particle shape remains unchanged. Full lines assume that the collapse begins when S = 0.33 (from Labrum[23] Figure 4)

Measurements by dual-polarization radar show that the value of the complex correlation factor ρ decreases in the melting layer. This factor is a measure of the degree of common alignment of the particles in the radar beam. This lower value of ρ indicates that the particles within the melting layer are more randomly orientated than those above or below it. Thus, the orientation of the particles do not contribute to the enhancement of the radar signal from the melting layer.

4.4 Processes in Zone 2

If the bright band signal decreases more than 6 dB in Zone 2 of this model, there must be some process leading to this extra decrease. One possibility is a break-up of water droplets with diameters in excess of 5 mm, a very realistic possibility. A breakup of 5-mm water droplets into 5 equi-volume droplets would result in a decrease in intensity of approximately 7 dB. Another possible process in Zone 2 is concerned with the shedding of meltwater. Since shedding for the large ice particles does not begin until 20 or 30 percent of the mass has melted, for the most part, this shedding process occurs in Zone 2 and results in a decrease in signal intensity.

5. CONCLUSION

The melting layer remains a crucial area within a cloud system. A thorough study using surface observations, radar observations, and aircraft flights would be of great benefit to the scientific community.

The AFGL study provided new information on the way in which ice crystals melt and the way radar views the melting layer. The literature survey, which is found in Appendix A of this report will be a valuable starting point for any future study of the melting layer. Other observations resulting from the program follow.

5.1 Ice Crystal and Snowflake Melting

Snowflake and ice crystal melting were observed and the observations were compared to theories.

Among the observations were the following:

(1) Snowflakes melt at a rate slower than that predicted by theory.

(2) Although snowflakes generally do melt from the outside in, they may do so in an irregular manner.

(3) The vertical stability of a snowflake depended upon its size and shape.

(4) A crystal will generally not form a single droplet; rather, it will split into several droplets.

(5) The speed with which a crystal melts will vary with its size. Small crystals will melt faster, however, all crystals larger than 3 mm will melt in about the same time.

(6) The rate at which snow pellets melt in the atmosphere is influenced by air temperature, relative humidity, snow pellet size and density.

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5.2 Radar Observations

Further examination of radar data concerning the melting layer, and new information available since 1981 have led to the following update of the findings reported in Appendix E of Schaller et al. [1]

The increase in the radar signal intensity in the so-called bright band can be explained by the following processes:

(1) The complex index of refraction for ice crystals $|K_i|^2 = 0.180$ on melting changes to $|K_w|^2 = 0.930$ for water.

(2) Any process which causes a growth in the mass of particles or aggregation in the melting zone would increase Z, the radar reflectivity.

(3) The shape and orientation of the particles in the bright band do not increase the radar echo intensity in the main channel of the receiver.

The following processes tend to decrease the radar echo intensity in the bright band:

(1) The increase in fall velocity of the melted particles decreases the number of scatters in the radar beam.

(2) The break-up of water particles with large diameters decreases Z, the radar reflectivity.

(3) The shedding of meltwater by the large particles decreases Z the radar reflectivity factor.

The size of the particles in the melting layer in this review are assumed to be small in size compared to the radar wavelength that is,

α = size parameter

$$\alpha = \frac{\pi D}{\lambda}$$

where

D = diameter of particle

λ = wavelength of incident radiation .

When $\alpha < 0.13$ Rayleigh approximation applies, we assume Rayleigh scattering. The correctness of this assumption is very evident in calculations with partially melted snow. For a surface rather than a mass relationship, the returned radar signal was calculated to be much larger than actually observed, while for a mass relationship theory agrees well with observations.

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Appendix A

This reference list adds 50 entries to Appendix A of AFGL-TR-82-0007. For the reader's convenience, the entire list is included. The list is in alphabetical order.

The rating system used in the aforementioned report is also used here. The numbers in parenthesis after each entry indicate the relevance of information as follows:

1. VERY RELEVANT   - Contains much helpful information.
2. SOMEWHAT RELEVANT - Has some valuable information.
3. POSSIBLY RELEVANT - Parts may be useful.
4. NOT VERY RELEVANT - Of limited use; may provide background material.
5. NOT RELEVANT   - Not directly applicable.

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